

THE MULTI-DIMENSIONAL NATURE OF WIND SHEAR INVESTIGATIONS

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I. Introduction

You may ask, "What's new about wind shear? Hasn't it been with us for a long time?" Yes, it has been around a while and it has always been something less useful than a pilot's best friend. It certainly is difficult to imagine there is anything really new about this rather common phenomenon. Perhaps it's a greater awareness of an old problem. Without considering other factors, wind shear is generally little more than a nuisance; an increase in the pilot's workload or an occasional firm landing announcing arrival at destination to an anxious passenger. Then why should we get so concerned about such a common atmospheric disturbance? Doesn't the system which has worked well in the past still provide for performance and control margins to accomodate disturbances or at least provide an alternative for the pilot? Yes, the margins are there and the system is reasonably good. The long term records so indicate. But recently, the records are also beginning to indicate something else.

Within the past few years, we are beginning to understand the various ways in which the wind shear nuisance can develop into a serious destructive force, especially when the approach and landing scenario includes serious pilot workload factors in combination with deceptive shears.

The influence of limited flight visibility and other localized weather phenomena, the effects of time constraints on the flight crew and terminal landing acceptance capacity, and even the runway surface condition are very important. They all have a bearing on either the performance required of the flight crew encountering a shear or the options available to cope with the ensuing situation. However, one additional factor, which is probably the most serious, is the lack of information (or lack of confidence in available information) on the existence of a low-level shear in the approach and landing area.

Not unlike many other forms of adversary encounter, the severity of a significant low-level wind shear is enhanced greatly by its element of almost total surprise. Given these considerations, the existing margins may not be sufficient to provide the options required for safe operation during shear encounters. Since 1971, there have been six air carrier accidents in which a low-level wind shear has been identified as a major factor. The impact of these accidents on the aviation community has resulted in a variety of investigations seeking to develop a better understanding of the wind shear phenomenon. The investigations often involve a multi-disciplinary effort supported by numerous government, institutional and industry organizations. Examination of a wide variety of related factors include such topics as wind shear characterization, aircraft/pilot performance in shear conditions, terminology and language development, wind shear forecasting, ground based and airborne wind shear sensor development, ground and flight wind shear displays, wind shear data collection and dissemination, and certainly not least of all, the investigations include pilot factors associated with wind shear encounters.

II. Today's Operational Scenarios

A look at today's operational scenario reveals that the introduction of the turbojet airplane into civil air carrier operations had rather broad implications to the wind shear problem. The increase in air traffic in our airport terminal areas, brought about by the wide acceptance of the jet transport, has not only increased the probability of an encounter with any particular low-level shear but it has significantly increased the workloads of the flight crew as well as the air traffic controllers. In addition, the turbojet airplane's sensitivity to wind shear appears to be greater than that of the propeller driven airplane due in part to its slower power response and slower aircraft acceleration. There appear to be very few compensating factors to lessen the severity of this weather phenomenon that are provided by the introduction of the turbojet airplane into the system. Because of these considerations, the operational pilot must develop increased astuteness and decision making capacity to cope with the increased workloads. The pilot's decision to continue or abandon an approach often requires a comparison of the results of a subjective evaluation in a deteriorating situation against the hard objective factors associated with a lengthy holding requirement or a diversion to alternate. His concern for justifying his decision to either himself or others may be no small factor in his decision making process. This is especially worthy of examination where erroneous cues are provided the pilot, as is possible, or even probable, in a wind shear encounter.

In its report on the June 24, 1976, John F. Kennedy International Airport (JFK) B-727 accident, the National Transportation Safety Board (Ref. 5) has stated in the analysis; "In summary, the accident involving Eastern 66 and the near-accidents involving Flying Tiger 161 and

Eastern 902 were the results of an underestimation of the significance of relatively severe and dynamic weather conditions in a high density terminal area by all parties involved in the movement of air traffic in the airspace system. The Safety Board, therefore, believes that no useful purpose would be served by dwelling critically on individual actions or judgements within the system, but that the actions and judgements required to correct and improve the system should be reviewed. All parts of the system must recognize the serious hazards that are associated with thunderstorms in terminal areas. A better means of providing pilots with more timely weather information must be designed."

111. Wind Shear Investigations

A. FAA Program Definition

As a result of the June 24, 1975 accident of Eastern Air Lines (EAL) Flight 66 at JFK and the August 7, 1975 accident of Continental Air Lines Flight 426 at Stapleton International Airport, the FAA has been investigating aircraft performance and control characteristics associated with low-level wind shears. In addition, it has begun an accelerated investigation of the various techniques available to detect hazardous shears in the approach and departure phase of flight operations.

An earlier FAA wind shear detection project has been initiated in 1972. The major objective of this effort was the development of ground-based sensors capable of measuring wind speed and direction to altitudes of 2000 feet AGL. Having been identified as a high priority effort in 1975, the **FAA** increased the level of activity from a single project to program level activity involving a number of projects, all of which are identifiable within the following six major task areas: Wind Shear Characterization; Hazard

Definition; Ground-Based Wind Shear Detection Systems; Airborne Wind Shear Development Efforts; Wind Shear Data Management; and, Integration of Wind Shear Systems and Data into the National Airspace System (NAS). The increased scope of the FAA wind shear program as defined by FAA report, FAA-ED-15-2, Engineering and Development Plan-Wind Shear (Ref. 1), includes an examination of all aspects and potential solutions for the hazards created by low-level wind shear.

Hazardous low-level wind shears are not adequately considered in the landing and takeoff criteria, either as a part of the Air Traffic Control system procedures or Federal Aviation Regulations or specifically addressed as part of the operating limitations requirements for the Airplane Flight Manual. Therefore, part of the wind shear investigation effort will be directed toward providing the FAA operating services with data on the capabilities of aircraft to cope with varying wind shear intensities at low altitude. This information could be used to determine the safe limits for arrival or departure conditions within the airport terminal area. It is also conceivable that some of the results may have an impact on future aircraft and system certification.

B. Assessment of Related Wind Shear Investigations

Prior to the implementation of the FAA Wind Shear Program, assessments were made of the various independently conducted investigations, observations, and experiments involving low-level wind shear. A continuous assessment is maintained, where possible, to assure the FAA efforts are maximized within the limitations of time and resources. Typical of the results of these assessments, the following limited descriptions illustrate the degree of diversification found in various independent low-level wind shear studies.

1. Accident Investigations

Accident investigative studies concerning wind shear characterization and its influence on pilot/aircraft control and performance have been greatly aided in recent years by the availability in operational aircraft of the inertial navigation system (INS) and digital flight data recorders (DFDR). When found in combination (usually limited to wide bodied turbojet airplanes engaged in long range, over water operations), these two devices can produce sufficient data to provide reasonable approximations of the pertinent atmospheric activities and aircraft flight profiles.

While it is possible to establish the physical contributions to approach and landing accidents from the relationship of the atmospheric activity to the flight profile, an assessment of the human factors which influence the pilot behavior must also be accomplished. The dependence upon the recall of piloting experiences to provide sufficient assessment of these factors, especially during low visibility, weather-related approach and landing operations, has not always proved adequate. Further examination through highly controlled experiments has been found to provide additional insight into pilot/aircraft performance interface. For these examinations, use has been made of highly sophisticated flight simulators which combine the capability to simulate the particular atmospheric disturbance with the appropriate visual external cues. Under these conditions, it is possible to replicate the various cockpit scenarios for detailed examination.

Early results of the use of INS/DFDR data to reconstruct the atmospheric dynamics and support flight simulation investigations of wind shear can be found in the National Transportation Safety Board (NTSB) report (Ref. 3) on the December 17, 1973 Logan International Airport DC-10 accident.

Through use of a McDonnell Douglas DC-10 simulator, the NTSB has been able to simulate the approach and landing environmental conditions that existed at the time of the accident. Flight scenarios were developed and flown in the simulator by a variety of subject pilots. The results of these experiments provided a verification of the existence and contribution of influencing physiological factors during the pilot's transition from instrument to external visual reference during certain types of wind shear encounters.

The atmospheric dynamics which existed at JFK on June 24, 1975 (Ref. 5) between 1944 and 2009 GMT have also been the subject of rather extensive investigations. During this time period fourteen aircraft either landed or attempted to land on Runway 22L at JFK. Of these, EAL 66, a B-727, descended the glide slope to approximately 400 feet where it encountered heavy rain and a down draft, referred to as a "downburst" by Fujita (Ref. 2), of such magnitude that the aircraft contacted the approach lights, impacted the ground and came to rest short of the landing Runway 22L.

The reconstruction of the atmospheric dynamics representative of the EAL 66 encounter required an extensive analysis (Refs. 4 and 5) and considered data from the following flights in addition to EAL 66:

- Flying Tiger Flight 161, a DC-8 that preceded EAL 66 on the approach by 8 minutes and 59 seconds;
- Eastern Air Lines Flight 902, a L-1011 that preceded EAL 66 on the approach by 7 minutes and 28 seconds; and,
- Finnair Flight 105, a DC-8 that preceded EAL 66 on the approach by 6 minutes and 45 seconds.

Based on these available data, wind models were constructed separately by The Boeing Company, the Lockheed California Company, the Douglas Aircraft Company, and the National Aeronautics and Space Administration (NASA). A selection of three of the resulting wind models were programmed into a Boeing Company B-727 engineering simulator for an examination of the dynamic effects of these reconstructed winds on the total performance of a pilot/airplane combination. The NTSB identified objectives of the simulator tasks were: "(1) to examine the flight conditions which probably confronted the flight crew of EAL 66, and (2) to observe the difficulties that a pilot has in recognizing the development of an unsafe condition and in responding with appropriate corrective action." When plotted as a function of distance from the runway, several of the airspeed and altitude traces recorded during the simulated approaches closely resembled the traces on the EAL 66 flight recorder.

In addition to the NTSB manned simulation experiments described above, other simulation experiments, conducted in the past 2-3 years, have combined wind shear and reduced visibility to assess pilot performance in approach and landing maneuvers. These include a joint USAF/FAA Low Visibility Simulation Program at Wright-Patterson AFB, Flight Dynamics Laboratory (Ref. 8) and a Douglas Aircraft Company experimental simulator study program (Ref. 7). The conclusions gained from these experiments indicate that effective pilot decision-making studies on the combined influences of low-visibility and wind shear encounters could be accomplished in current state-of-the-art simulation.

2. Atmospheric Studies Associated with Flight Operations

Extensive analyses of satellite, radar and synoptic weather radar have also been performed (Ref. 2) and correlated with wind models and other data resulting from the EAL 66 accident investigation. With this information Dr. Fujita has developed a model of the spearhead' storm and downburst cells² associated with the EAL 66 accident. Figure 1 depicts three significant downburst cells (DBC) in relation to the time-space coordinates of the paths of arriving and departing aircraft at JFK Runway 22L. It is interesting to note the existence of a sea breeze front situated along a line nearly Perpendicular to the runway at about the glide path intercept point. The out flow from the downburst cells was distorted by the sea breeze front, resulting in strong out flow winds to the north of the front. Since most of the airport was under the influence of the sea breeze, the official wind instrument used to select the landing runway was indicating the surface wind was most nearly aligned with Runway 22L. Strong support for additional wind sensors around the perimeter of the airport, as provided in the FAA ground-based wind shear detection system development plan, can be developed from these detailed studies. The thunderstorm gust-front activity that figures in the Continental Air Lines Flight 426 accident at Stapleton International Airport also supports the need for additional wind sensors.

1. Spearhead (echo)- a radar echo with a pointed appendage exceeding toward the directions of the echo motion. (Byers and Fujita)
2. Downburst (cells)- a localized intense downdraft with vertical currents extending a downward speed of 12 fps at 300' above the surface (Byers and Fujita).

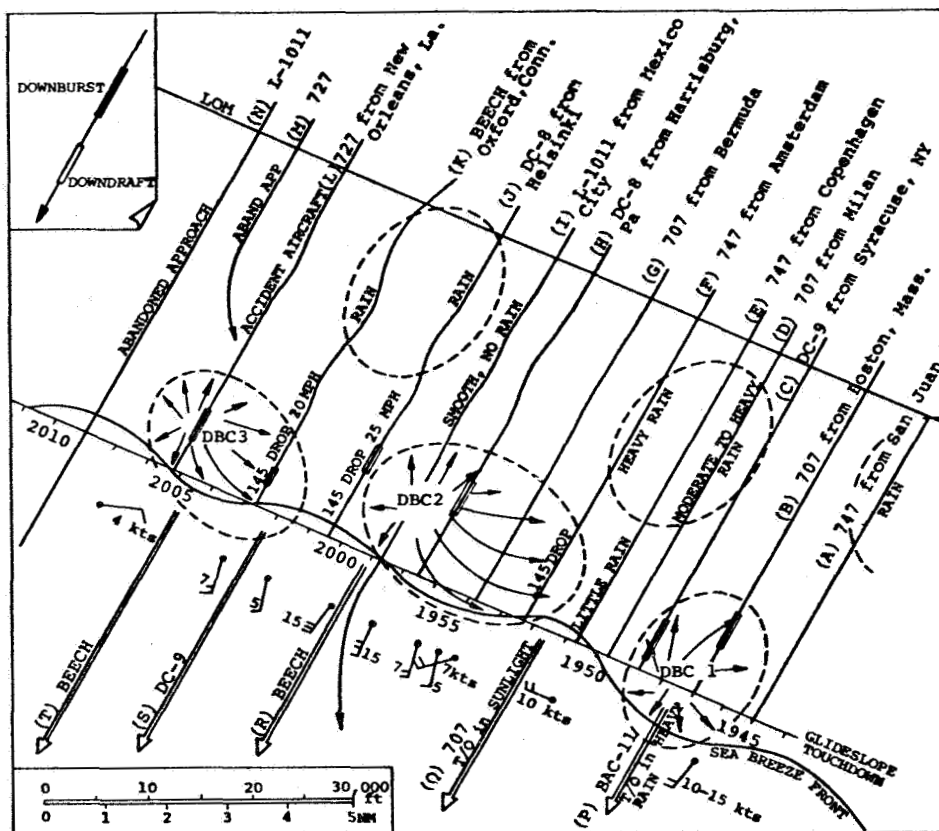


Figure 1 Three Downburst Cells (DBC) Depicted on Time-space Coordinates, DBC 1 was on the Runway Threshold and DBC 2 Affected Seriously the Approach Effort of Aircraft "H" and "I" DBC 3 Blew Aircraft "L" Down to the Ground, 2000 ft. Short of Runway 22L
(Fujita 1976)

Other atmospheric studies and assessments on low-level wind shear include a rather extensive data collection and wind shear characteristics comparison by Northwest Orient Air Lines (NWA). For several years, the NWA flight crews and meteorologists have maintained a two-way reporting system which has provided observational data on the presence of wind shear and turbulence throughout the NWA route structure. Sowa (Ref. 6) has developed the data collected during 70 cases of NWA wind shear encounters into a wind shear versus turbulence comparison. These data were plotted against two low-level wind shear forecasting parameters, speed of the front and temperature differences across the front. The resulting plot provided the basis for developing the nomogram, Figure 2, which can be used to indicate to flight crews whether wind shear will be smooth or turbulent.

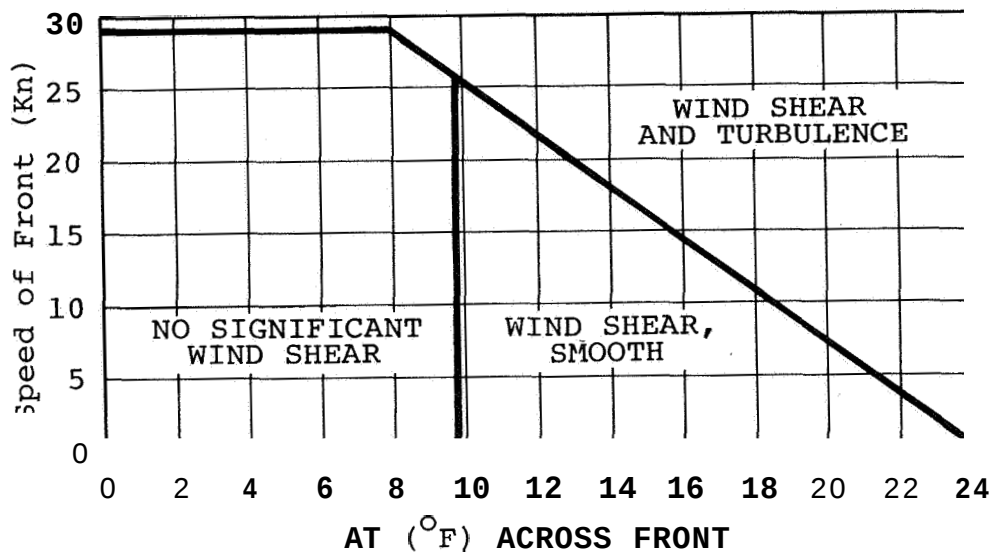


Figure 2 Wind Shear Forecast Nomogram
(COURTESY NORTHWEST ORIENT AIRLINES)

The FAA wanted to determine the validity of the nomogram to support forecasting the wind shear. It assigned the task to a joint USAF/FAA **All** Weather Landing Project operating a C-141 airplane into Category III weather. The task objective included, in addition to determining the validity of the forecasting technique, a requirement to determine what levels of wind shear (if any) could be found in the very low visibility (down to Category IIIB) landing condition. The results indicated that the **NWA** forecasting technique, based on the use of the nomogram criteria, has sufficient validity **to** warrant its use in an expanded forecast evaluation project. The results also provided data showing the presence of significant levels of wind shear in combination with very low visibility.

C. FAA Wind Shear Program Establishment

In establishing a wind shear research and development program within the FAA, one of the requirements was the need for an early product which could be used to provide near-term alleviation of the wind shear hazard, even if only in a limited degree. Therefore, implementation of any near term results is a priority requirement reflected in many of the following major task areas.

1. Wind Shear Characterization

Early deliverables from this task area involved the development of four wind shear profiles for use in various fast time and manned flight simulation projects identified in other task areas. The use of a common set of profiles in the various simulation efforts is providing some measure of comparability between the separate efforts. The profiles used provide a range of wind shears from mild changes in the along track wind components to shears with direction and speed changes, and one which also includes changes in the vertical wind component.

These include:

- a neutral wind shear profile, Figure 3, which represents wind conditions in a highly mixed atmospheric boundary layer when temperature stratification is consistent with adiabatic distribution ($9.8^{\circ}\text{C}/\text{KM}$);
- an inversion wind shear profile, Figure 4, which is representative of a low-level temperature inversion overlaid by fairly strong winds immediately above the inversion;
- a frontal wind shear profile, Figure 5, which is representative of a fast moving frontal zone producing significant turning of the wind vector with altitude; and,

- a thunderstorm wind shear profile, Figure 6, which is representative of a thunderstorm cold air outflow pattern producing abrupt changes in both horizontal and vertical wind velocities.

The longer term objective of this task consists of research into the meteorological conditions that cause hazardous low-level shears, its life cycle manifestations and its climatological and geographical distribution. FAA-sponsored work in this area is being performed by NOAA's Wave Propagation Laboratory (WPL), NOAA's National Severe Storms Laboratory (NSSL) and the Space Sciences Laboratory of NASA's Marshall Space Flight Center (MSFC)

2. Hazard Definition

The primary objective of this task is to establish the wind shear hazard potential in terms that are meaningful and useful to pilots. It embodies a requirement to express the hazards in a standardized operational/technical language based on the hazard being defined in terms of altitude, aircraft type (or category) airspeed, configuration, gross weight, etc. The task is divided into the following sub-tasks:

- a. Computer simulation of Aircraft Response to Wind Shear-In a joint effort between FAA and NASA Ames, a comprehensive review of aircraft response data is being made to determine the critical aerodynamic and performance characteristics of aircraft based on given atmospheric dynamics of wind shear activity. Fast time simulation of wind shear encounters will be conducted using models of generic aircraft types.

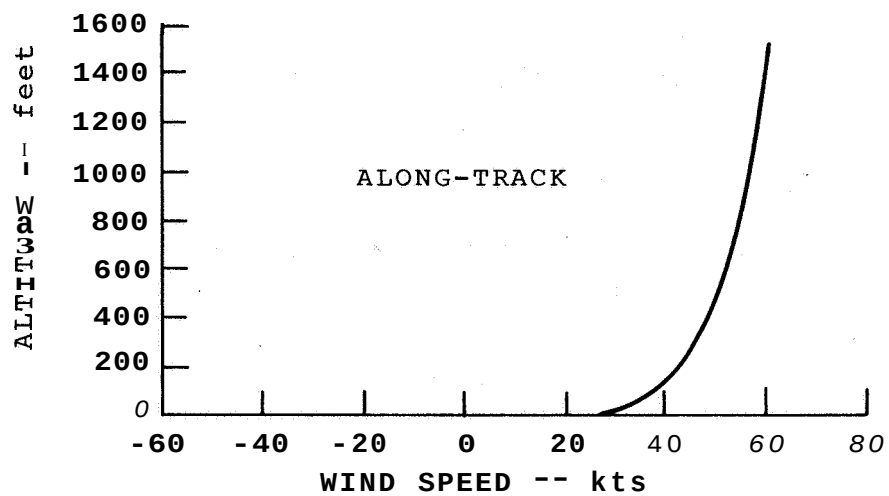


Figure 3 Neutral Wind Shear Profile

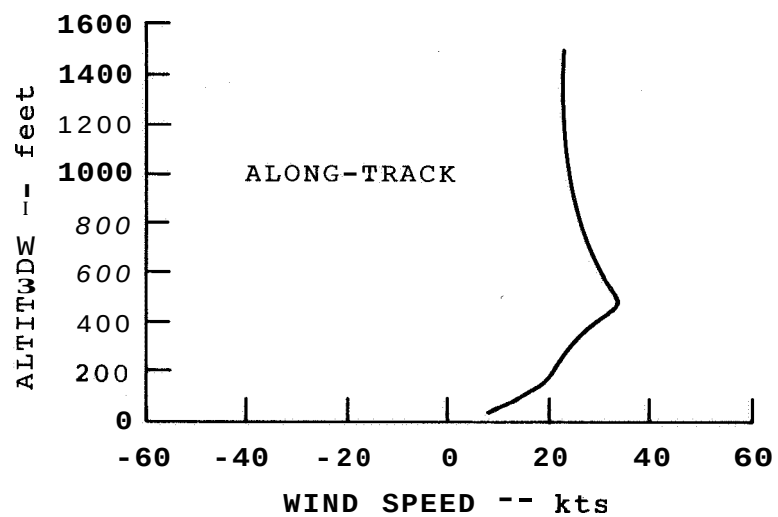


Figure 4 Inversion Wind Shear Profile

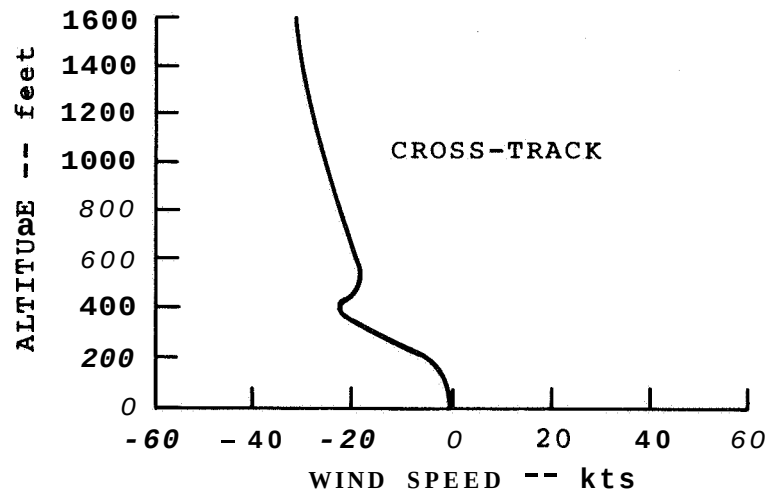
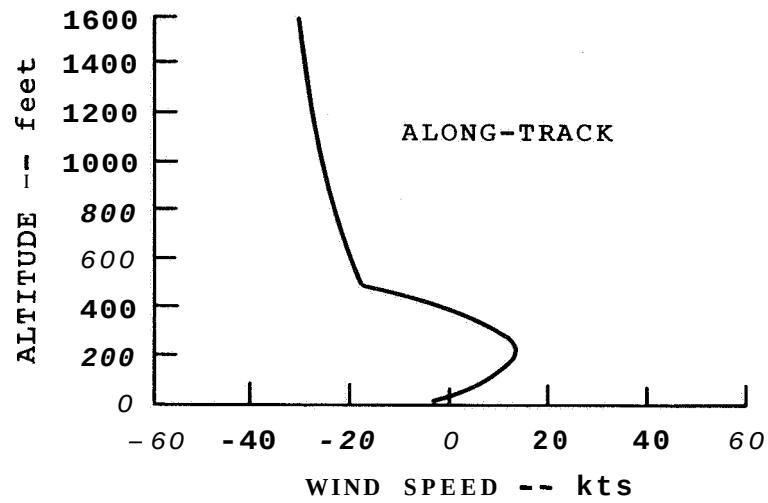


Figure 5 Frontal Wind Shear Profile

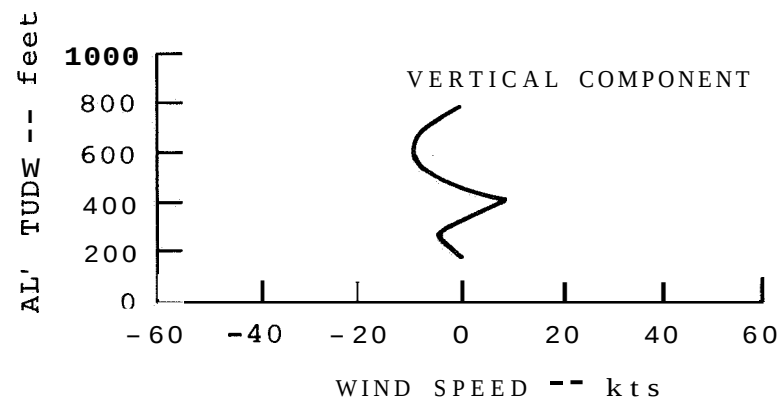
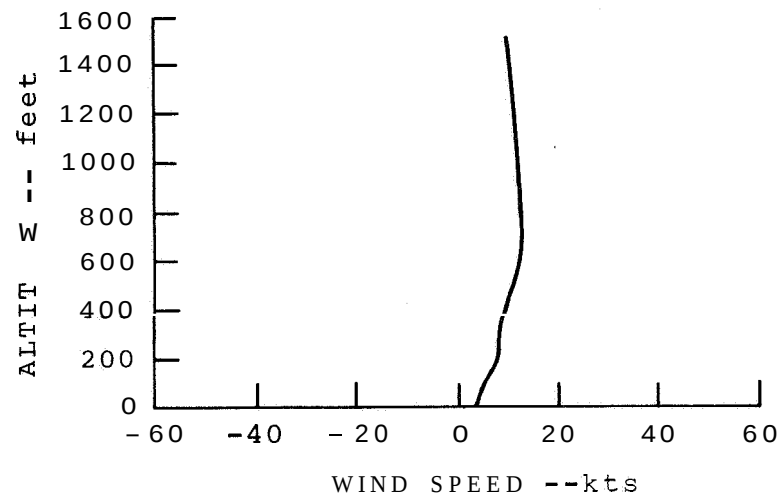
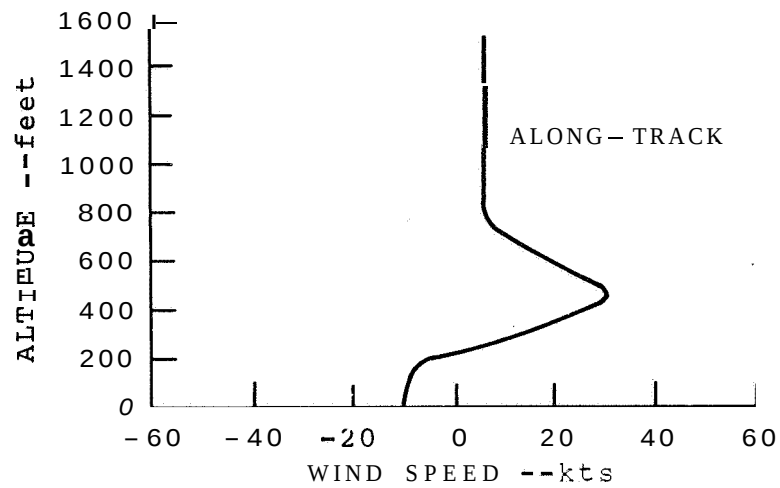


Figure 6 Thunderstorn Wind Shear Profile

- b. Accident/Incident Analysis- The objectives of this task is to examine a broad segment of the existing aviation accident records to identify wind shear factors which may have been a contributing factor to an accident. These factors will be used to establish a wind shear hazard profile.
- c. Language Development- At present, there are misinterpretations of the technical terminology used by engineers, meteorologists and pilots to describe wind shear, and there is no commonly accepted operational wind shear terminology for use by pilots and controllers. For example, in the literature some call a horizontal wind which changes as a function of altitude a "vertical" wind shear and some call it a "horizontal" wind shear. Pilots and controllers have had no common terminology for a shear which causes a decrease in the aircraft's airspeed as opposed to a shear which causes an increase in airspeed.

It is obviously desirable for a pilot who has just encountered a wind shear to report the event before a following aircraft encounters the shear (on either arrival or departure). Also, it is equally desirable that the pilot of that succeeding aircraft understand precisely the terminology of the transmitting pilot and the type of the wind shear encountered.

The objective of this task is to develop standardized terms to be used operationally to communicate the necessary information to assist pilots in avoiding or coping with a shear on approach or departure.

3. Ground-Based Wind Shear Detection Systems

Wind sensors which range in complexity from single anemometers to elaborate and complex microwave, sonic, and laser probes are being evaluated for use in ground-based shear detection systems.

- a. Barometric Systems- Since 1973, four out of six wind shear related air carrier accidents have occurred when thunderstorms have been in the vicinity of the airport. Therefore, thunderstorm gust front detection has been assigned a very high priority in the FAA wind shear program.

To accomplish the gust front detection, the characteristic pressure change that precedes a surface wind or temperature change is detected with pressure-jump sensors located in arrays adjacent to the airport. The warning provided by these detectors will be used to inform arriving and departing flights of an impending or potential gust front encounter. At present, gust front warning systems (GFWS), consisting of arrays of pressure-jump sensors (PJS) have been installed at the Chicago O'Hara airport and the **NSSL** WKY-TV meteorological tower at Oklahoma City, Oklahoma. **PJS** are also being installed at Dulles International Airport (IAD) .

- b. Anemometers- At O'Hare and NSSL, anemometers have been installed in conjunction with **PJS** to provide additional information about the surface strength and duration of thunderstorm gust fronts.
- c. Acoustic Doppler Systems- The Acoustic Doppler systems have been used primarily as research tools to vertically probe the atmosphere and provide wind speed and direction data at low altitudes. Their major operational limitation is that this vertically looking system can only provide data over one small zone above the transmitter. Because of the large areas of major airports, wind conditions reported by the acoustic sensor may be significantly different from those several miles away. Since the acoustic system is a comparatively high cost system there is some question concerning the number of sensors which could be economically employed at any one airport. Also, the system is unable to operate under heavy precipitation conditions. The use of a dual-sensor system, using a pulsed-Doppler radar during precipitation, is scheduled for testing at Dulles International Airport.
- d. Laser Systems- Doppler Laser systems for low-level atmospheric measurements fall into two classes: continuous wave (CW) and pulsed. The CW Laser system has a demonstrated capability to scan vertically and report wind speed and direction from the surface to altitudes of up to 1000 feet AGL. Up to this altitude they may also offer "all weather" capability at a cost comparable to or less than acoustic Doppler system without its pulsed Doppler backup. For this reason,

the CW Laser's potential capabilities will be investigated for near term airport implementation.

The pulsed Laser has a much greater range than the CW Laser and therefore may be used to scan up the glide slope. This ability appears to be a most desirable method of providing wind shear data.

The pulsed Laser approach, although offering a greater range capability, can only be pursued in a longer term development program.

- e. Radar Systems- The potential of microwave radars is presently being evaluated to determine their ability to make wind shear measurements under "all weather" conditions. Their radar scanning capability could provide greater volumetric sampling than overhead vertical probes such as an acoustic Doppler sounding system. This area of the program plan is also viewed as a longer term effort.

4. Airborne Wind Shear Development Efforts

Ideally an airborne system for aiding a pilot to cope with shears should be predictive in nature. This is especially true for the severe shears where aircraft performance margins have been virtually eliminated. The timeliness of wind shear information is a basic consideration. The system must be free from ambiguous interpretation and its impact on flight crew work loads must be carefully considered.

To aid in the evaluation of specific pilot aiding concepts, it is necessary to identify the various roles which an airborne wind shear detection and/or information system could fulfill.

Advisory-Alerting a pilot of an impending potential dangerous shear, if accomplished in sufficient time has been demonstrated in simulation experiments to be an effective aiding concept. It is especially helpful if the type of shear is also identified to the pilot. A word of caution- the credibility of this concept must be established and maintained. The pilot must have confidence in the information given.

Detection- To be assured of a shear detection during an encounter while using conventional instrumentation requires a very astute, attentive, pilot. If the detection concept is based on panel-mounted (head down) displays and unless it has some degree of predictive characteristic, it could adversely impact the crew workload, in which case some automation might be in order. If the shear has been encountered after the pilot has transitioned to outside visual references, some forms of head-up displayed information have been shown to have merit.

Airspeed Management- This role is of major importance since it provides the means of maintaining sufficient kinetic energy with which recovery from a severe shear can be accomplished. The airspeed management role should have predictive capability and must be based on a rationale which considers limiting flap speeds and aircraft landing performance.

Flight Path Control- This role could possibly provide the pilot with a form of improved pitch guidance following a shear encounter. However, the mechanization of flight path angle must avoid the use of terms which are affected by vertical wind components, otherwise erroneous indications can be expected.

One of the objectives of the FAA wind shear airborne equipment task has been a survey and evaluation of existing and developmental airborne systems, procedures and techniques to determine the effectiveness in reducing the wind shear hazard. While we are aware of various developmental efforts underway by the industry we have not had the opportunity to evaluate all of these because of budgetary limitations or proprietary reasons. However, there has been a number of recommendations made regarding the potential of various state-of-the-art concepts to wind shear alleviation. Many of these recommendations appeared to have sufficient merit to warrant examination in a controlled experiment.

- a. Manned Flight Simulation Experiments- Prior to any decision to develop new avionic equipment for wind shear detection/display, it was necessary to evaluate pilot performance and response to shear encounters while being exposed to the various aiding concepts referenced above. To accomplish this evaluation, a series of flight simulation experiments are being conducted for the FAA through a contract with Stanford Research Institute (SRI). The first simulation effort was designed to provide an early determination of the potential operational effectiveness of candidate systems and techniques that could be used to guide in-depth studies and

systems refinement. These experiments were conducted in a DC-10 simulator at the Douglas Aircraft Company Flight Crew Training Center in Long Beach. The simulator was equipped with a full complement of controls and instruments for all flight crew member positions and was capable of simulating all flight guidance and control modes available on the aircraft in service use. In addition to the six degrees of freedom motion system it was equipped with a Vital III computer generated imaging system for representing the external visual scenes. The wind shears represented by the profiles in Figures 3, 4, 5, and 6, were programmed in the computer along with a moderate level of turbulence.

In Phase I of the simulation effort, pilot performance data and subjective pilot opinions were recorded on eight highly experienced pilots most of whom held DC-10 pilot qualifications. The pilots were subjected to various flight scenarios and wind shear combinations while being aided by the following concepts presented separately:

- Wind shear advisories based on ground sensor data;
- Panel display of groundspeed versus vertical speed for a 3" glide slope;
- INS wind speed and direction;
- Panel display of groundspeed integrated with conventional airspeed indicator (AV) (Figure 7);

Panel and head-up display of difference between along-track wind component at surface and aircraft altitude (ΔV_w) (Figures 8 and 11); and, Panel and head-up display of flight path angle and potential flight path angle (Figures 9 and 10).

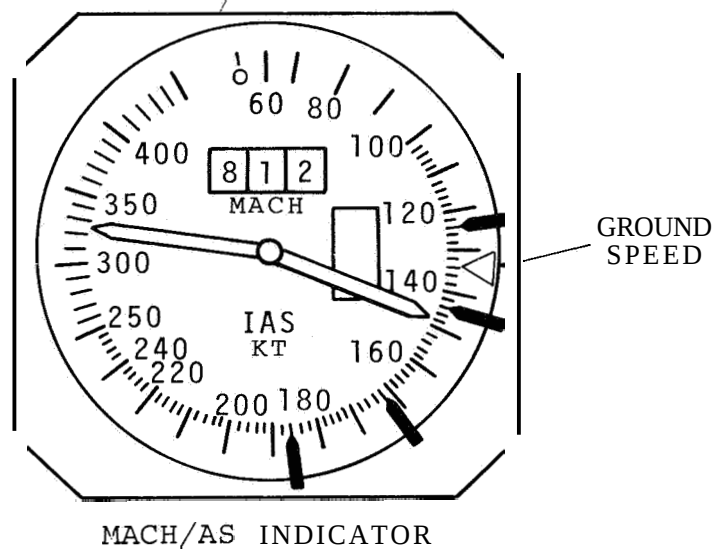


Figure 7 Test Display of Ground Speed

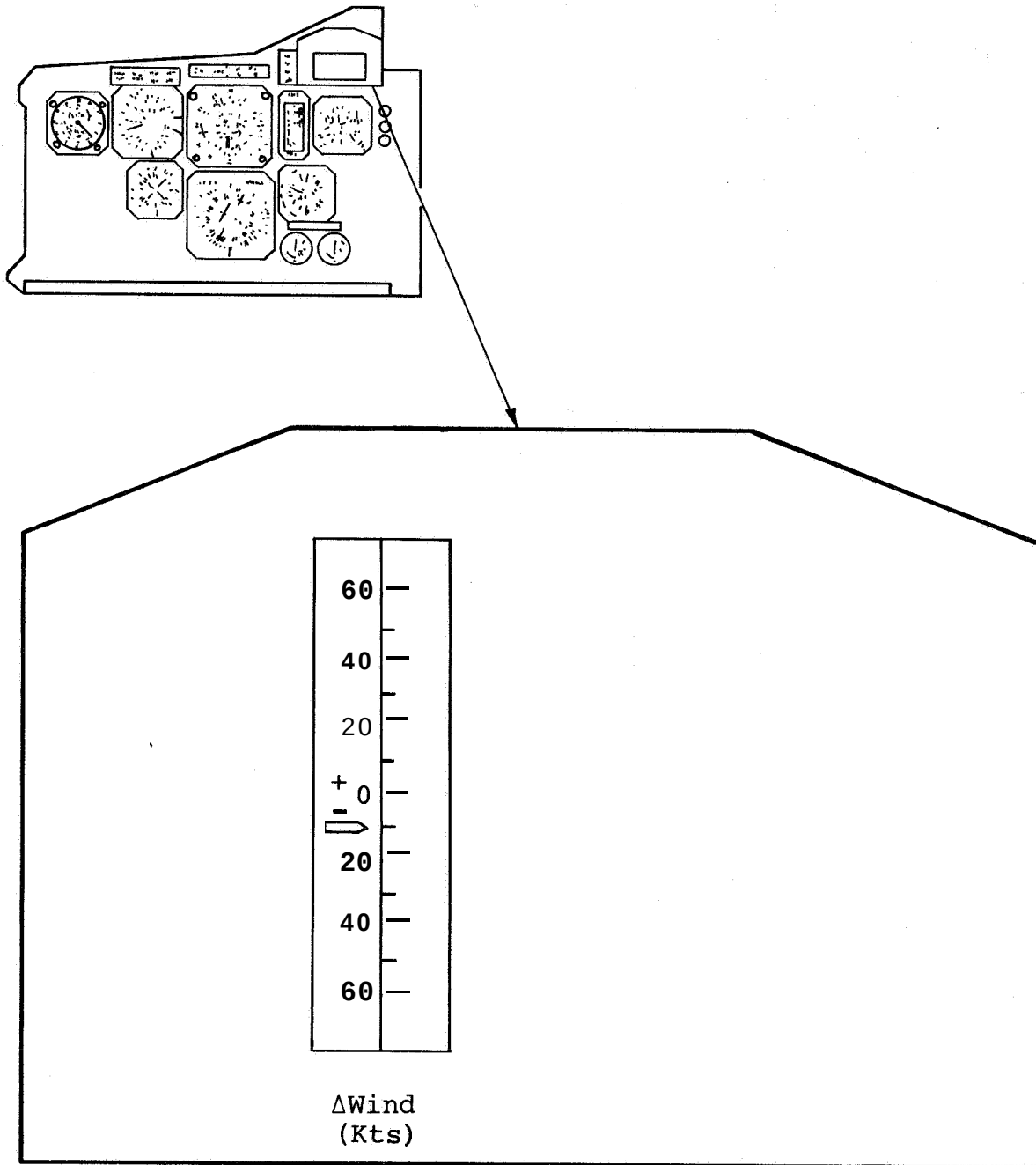


Figure 8 Test Display of the Wind Difference Indicator

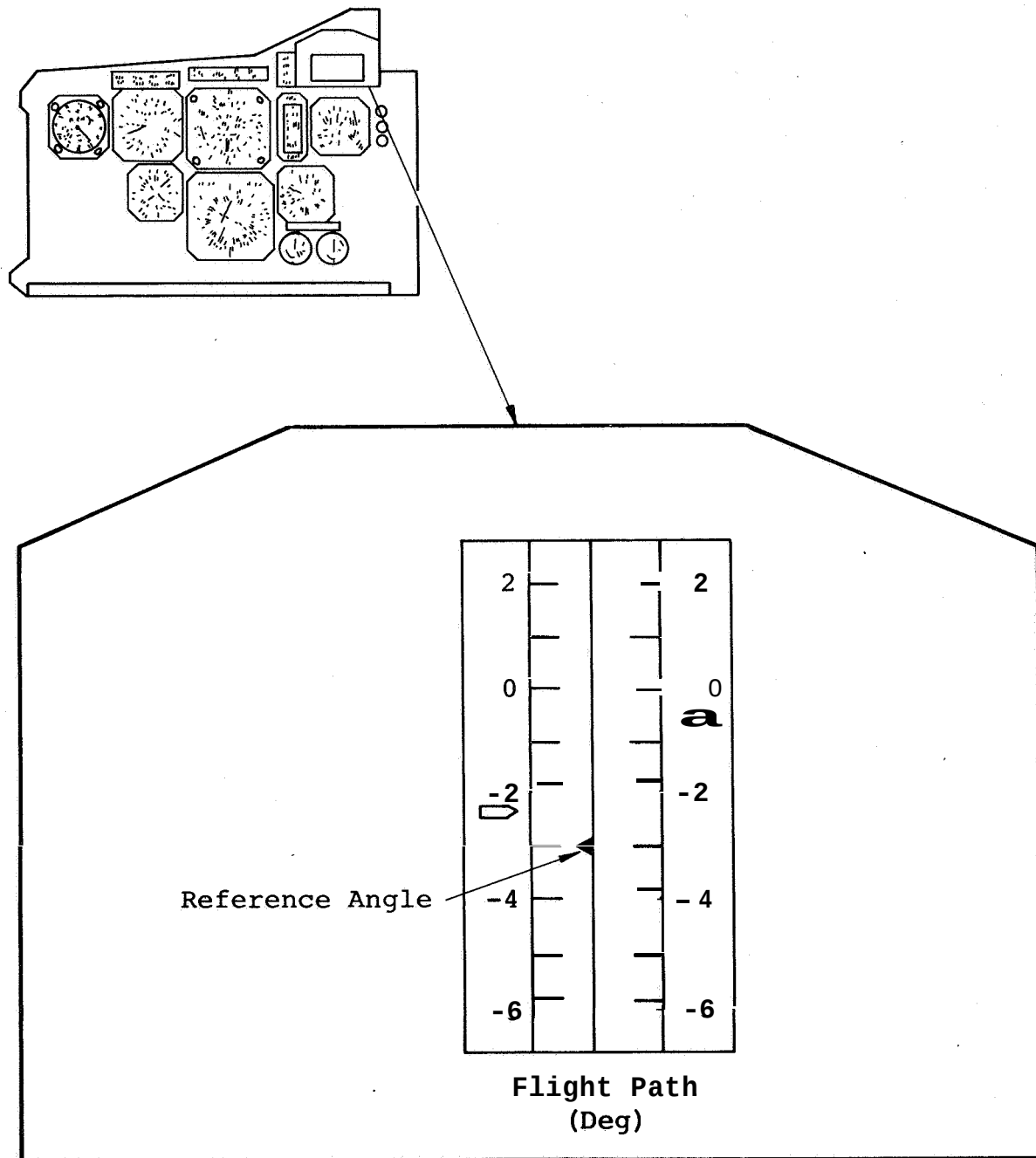


Figure 9 Panel Display of Flight Path Angle (Left) and Potential Flight Path Angle (Right)

Aircraft Symbol

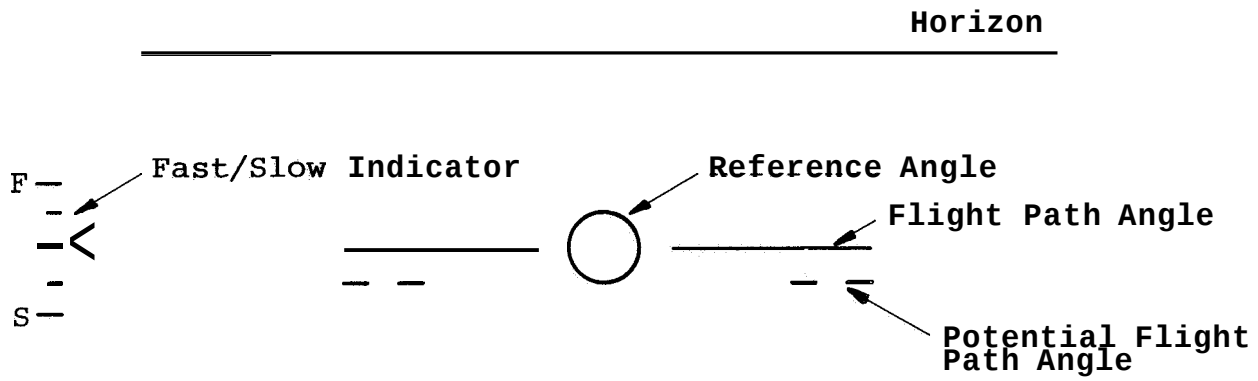


Figure10 Head-up Display Format for Phase 1 Testing

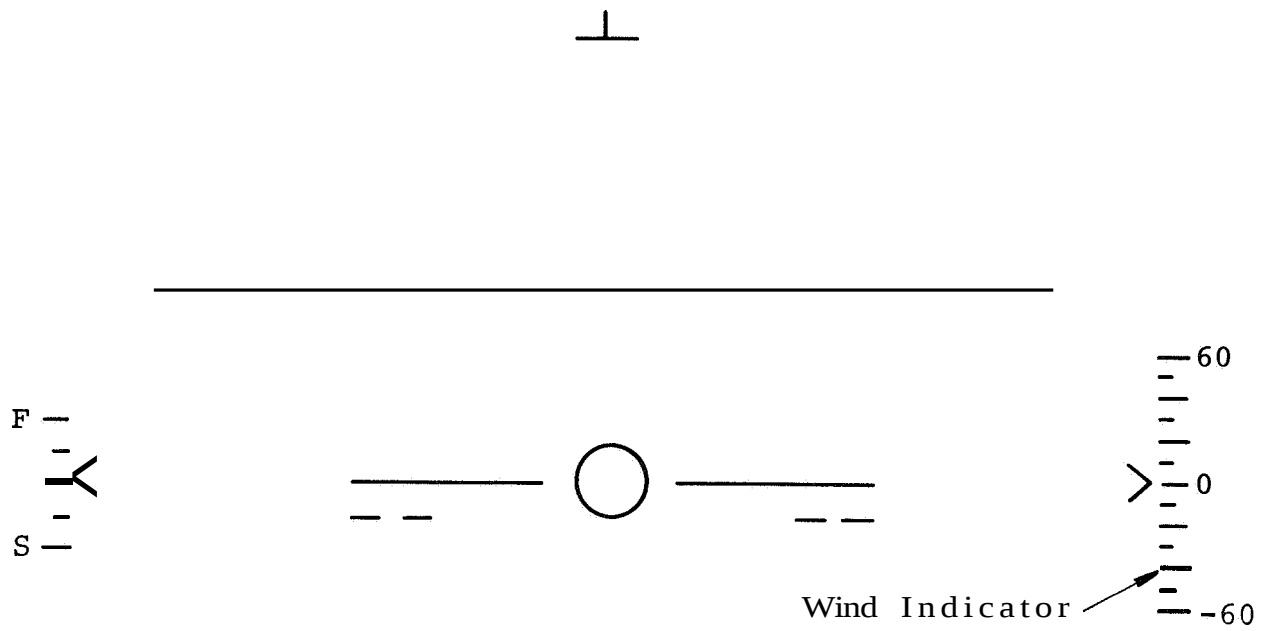


Figure 11 Head-up Display with the Wind Difference Indicator

- b. Results of Airborne Experiments- The results of these experiments indicate the groundspeed/airspeed comparison (AV) ranked as the best aiding concept by pilot subjective opinions and by the comparison of recorded landing performance. The second ranking aiding concept was found to be the along-track wind component comparison (ΔV_w), particularly when presented in a head-up display. There is also an indication that the head-up displayed flight path angle has some merit. The role of head-up displays for wind shear detection will require additional study.

The AV and ΔV_w concepts assume the availability of accurate, timely groundspeed information in the airplane. For those aircraft so equipped, INS can provide this function. As a priority development, the FAA has efforts underway to develop a less costly method of obtaining the ground speed (closure rate) within the accuracy and time delay requirements. For the four shears examined in both manned and fast-time simulation experiments, the results indicate that a sensor lag of up to 5 seconds can be permitted on the groundspeed signal. The accuracy limits have not been established since velocity errors in addition to the 5-second delay have not yet been programmed in wind shear simulation experiments conducted by the FAA. In addition to the groundspeed input accurate wind information from the runway threshold area must also be available.

- c. Operational Use of Groundspeed Augmented Wind Shear Detection Systems- The mass of the airplane precludes its inertial velocity from changing rapidly. But because of mass, the airspeed changes due to shears can occur almost instantaneously. Monitoring the relationship between the inertial velocity (groundspeed or closure rate, for all practical purposes) and airspeed provides a technique for aiding wind shear encounters.

The ΔV groundspeed information, displayed on an airspeed indicator mechanized through a controllable speed "bug" or through the use of an additional needle, is used in conjunction with a minimum groundspeed reference. The minimum groundspeed reference value is derived from approach speed TAS minus the along-track wind component at the threshold. In use, the pilot never allows either airspeed or groundspeed to drop below their respective reference approach speeds.

The ΔV_w concept uses a display (Figures 8 and 11), which indicates a value representing the surface along-track head wind component minus the flight level along-track head wind component. A negative value indicates the presence of a shear between the aircraft and the runway, characterized by a decreasing head wind (or increasing tail wind). For negative values, the pilot should increase his approach airspeed by the indicated value. For positive values no decrease below approach airspeed would be made but the pilot is informed that a shear can be expected.

The positive value indicates an excess of total aircraft energy may occur at some point during the approach. While this situation may appear to be the least critical of the two cases, it shows indications in simulation experiments of being the most critical—simply because the pilot is deceived into making excessive thrust reductions to overcome the temporary indication of excessive airspeed and/or altitude. The longer term stabilized thrust requirement following a decrease in tail wind (or increase in head wind) is for increased thrust.

- d. Future Airborne Programs— Based on the results of the Phase I simulation experiments, the second phase of simulation to be conducted by SRI will be designed to accomplish the following:
 - (1) examine improved AV and ΔV_w displays;
 - (2) evaluate additional uses for flight path angle information, particularly where the dynamic effect of the wind shear causes misleading thrust cues to the pilot; and, (3) evaluate flight director and thrust command information made possible through acceleration augmented algorithms.A head-up display evaluation is also being pursued by the FAA, although the scope of this project goes beyond the time constraints placed on the wind shear program. The head-up display program; however, includes wind shear related considerations.

5. Wind Shear Data Management

The objective of the wind shear data management is to organize the airborne and ground-based meteorological data collected in the program for subsequent analysis and processing and to build a data base of wind shear information for use in the program. In addition to the ground-based sensors, met-towers, etc., a dedicated meteorological data collection airplane is employed to expand the sampling of various atmospheric phenomena.

6. Integration of Wind Shear Systems and Data into the National Airspace System (NAS)

There is a high priority placed on implementing the results of the wind shear investigations into the NAS. Wind shear displays, languages, advisory messages are subject to human factors analyses, testing and evaluation. Projects for these evaluations are underway.

IV. Conclusions

The solution to the wind shear hazard must depend on a variety of developments. It is quite probable that each of these developments will provide contributions to the total but none will provide all the solutions required.

The areas which show promise for short term solution are:

- Greater pilot awareness of wind shear through improved training.

- Improved forecasting for certain types of frontal shears.

- Airborne displays based on groundspeed/airspeed comparison.

- Improved gust front warning through ground-based sensors.

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